Soil Characterization for Fields Irrigated with Recycled Saline Drainage Waters

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Abstract: In California, it is estimated that 4.5 million acres are salt-affected—primarily on the Westside San Joaquin Valley (SJV). In addition to soil salinity, high water tables and boron toxicity are chronic problems for Westside SJV agriculture. Drainage water re-use is considered to be one of the more sustainable and environmentally responsible options for drainage management because the salt, selenium and boron are managed on-farm and do not go off-site to compromise water quality in nearby water bodies. In 1996, an Integrated on-Farm Drainage Management (IFDM) system was developed as a demonstration project at the Red Rock Ranch (RRR) out on the Westside SJV. For the past four years, one focus of our research at the RRR IFDM demonstration project has been the soil characterization of fields at the RRR. The major objective of the soil characterization is to assess the changes in soil salinity of fields subjected to irrigation with recycled saline drainage. Within the last year, we have been conducting infiltration studies in an effort to evaluate the effectiveness of surface applications of gypsum on infiltration rates of the fields receiving the recycled saline drainage water. From soil samples collected down to five feet, it is evident that in the areas receiving relatively better quality canal water, leaching is occurring as indicated by the relatively lower salinity at shallow depths. However, for fields irrigated with the most saline recycled drainage water, there is extreme salt accumulation and sodicity in the top foot of soil. Furthermore, the high degree of spatial variability of soil salinity inferred from non-invasive electromagnetic induction mapping suggests that there is need for more intensive soil management in the fields receiving the relatively higher saline drainage water. Preliminary results have indicated that steady state infiltrability rates averaged at 2.1 cm h^{-1} and 1.7 cm h^{-1} for the gypsum plots in areas receiving canal water and the recycled drainage water, respectively. For the non-gypsum plots, values ranged from 0.7 to 1.0 cm h^{-1} for both areas. Future research should continue to assess changes in the soil chemical and hydraulic properties of the fields at the RRR irrigated with the recycled saline drainage water.

Introduction: Historically, salinity has been a constraint to irrigated agriculture (van Schilfgaarde, 1990). In California, it is estimated that 4.5 million acres are salt-affected—primarily on the Westside San Joaquin Valley (SJV) (Letey 2000). The westside SJV is not in salt balance and the magnitude of the problem is revealed in the estimate of a net import of salt to the Westside in state and federal irrigation water projects (subtracting out natural drainage to the San Joaquin River) of 40 railroad cars daily (San Joaquin Valley Drainage Implementation Program, 1998). Furthermore, the region's soils are derived from alluvium originating from the once submerged coastal mountains and so they contain high concentrations of salts and elements typical of a marine environment (Letey, 2000). In addition to soil salinity, high water tables and boron toxicity are chronic problems on the Westside SJV. The combined Westside acreage that is drainage impacted (groundwater 5 feet or less from the surface) averaged nearly 500,000 acres in the last decade (SJV Implementation Drainage Program, 1998).

Both drainage and salinity compromise the profitability of Westside agriculture not only by reducing yields, but often by limiting crop choices to low value row crops rather than higher value, salt sensitive, vegetable crops. Furthermore, because of political, economical and environmental factors, the west side farmers are not allowed to freely discharge their drainage water. For example, as a result of the high selenium content of the drainage water that was responsible for migratory waterfowl toxicities, the Kesterson Reservoir was closed in 1986, thereby forcing the plugging of drain lines in the Westlands Water District that were contributing drainage flows to the reservoir (Letey et al. 1986).

Drainage water re-use is considered to be one of the more sustainable and environmentally responsible options for drainage management because the salt, selenium and boron are managed on-farm and do not go off-site to compromise water quality in nearby water bodies (Grattan et al., 1999, 1997). In 1996, a sequential drainage water re-use demonstration project, now called IFDM, was initiated at Red Rock Ranch (RRR) to test the feasibility of irrigating salt tolerant crops, forages and halophytes with drainage water so as to reduce its volume prior to discharge into a solar evaporation system. As designed in 1996 (**Figure 1**), high quality canal water (**Table 1**) is used to irrigate **Area A** that is in transition from low value row crops to higher value vegetable crops. Drainage collected from **Area A** plus tailwater is applied to **Area B** ***(1st re-use)*** containing salt tolerant row crops. Drainage from **Area B** is applied to **Area C** ***(2nd re-use)*** where salt tolerant forages are grown. The tertiary drainage (**Table 1**) is applied to **Area D** (***3rd re-use)*** where only halophytes are grown due to the high salinity and boron (ECe 30 - 50 dS/m and boron 25 - 50 mg /kg soil). Finally, the drainage is discharged into a solar evaporation system (1% land area) for rapid evaporation of water and precipitation of the salt.

Figure 1. Red Rock Ranch Sequential DW Re-use Demonstration Project as Designed in 1996

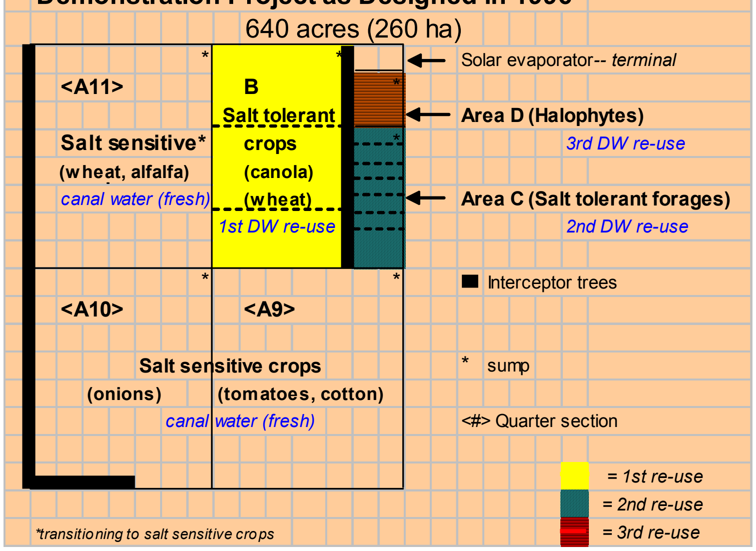
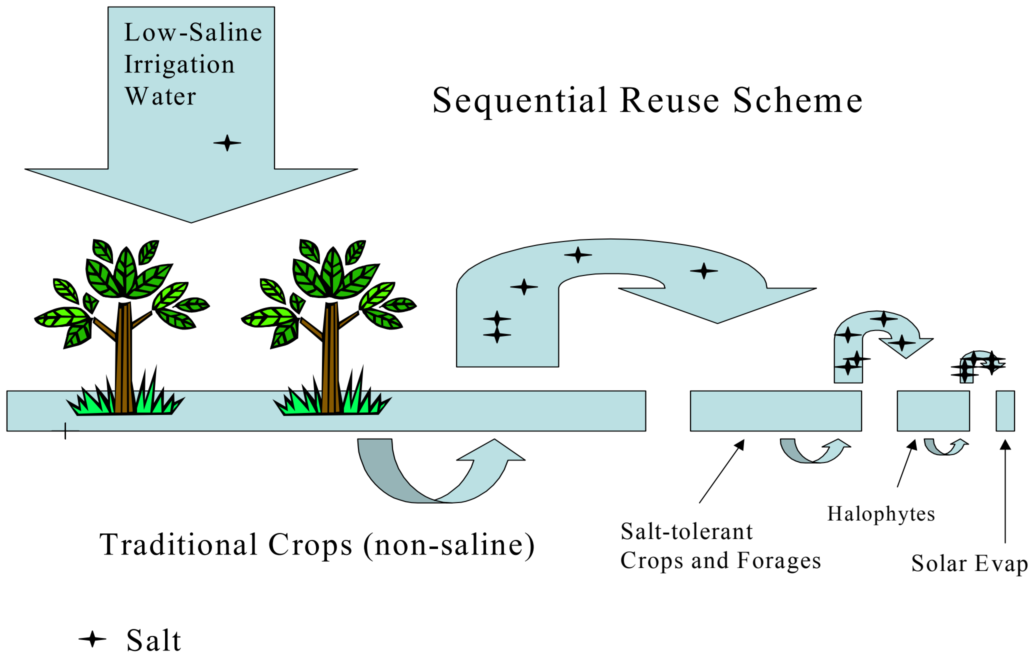


Table 1. Typical chemical composition of canal water used to irrigate Area A and concentrated drainage water used to irrigate halophytes in Area D.

Water	EC dS/m	SAR	pH	Na meq/l	Ca meq/l	Mg meq/l	Cl meq/l	SO_4 meq/l	B mg/l	NO_3–N mg/1	Se mg/l
Canal (Area A)	0.57	2.8	7.8	3.1	1.4	1.0	2.0	2.1	0.5	1.3	< 0.1
Drainage (Area D)	15	25	7.9	128	35.8	16.4	15.1	76.5	24	29	1.3

Figure 2. Theoretical function of sequential drainage water re-use.



The RRR IFDM demonstration project is serving as a venue to test the IFDM concept. It is still not proven that the sequential re-use can significantly reduce drainage volumes and that sufficiently high leaching fractions can be maintained at each stage along the sequence to move large amounts of salt and boron into the solar evaporation systems (**Figure 2**). Even though much research is still needed to validate this concept, new IFDM projects are slowly being undertaken by other Westside growers. Consequently, our current research is focused in three critical areas for the testing of IFDM systems:

- Water use (ET) of salt tolerant forages and halophytes that are candidates for IFDM;
- Productivity, and forage quality of the candidate species; and,
- Soil characterization and management for IFDM systems

Information on these topics is urgently needed by Westside growers who are looking to innovative drainage water management and reuse options such as IFDM, as a means of maintaining the profitability and sustainability of their farms.

Objectives: For the purpose of this paper, the focus will be only on our research dealing with the soil characterization and infiltration rate study. The main objectives of this component of our research are to:
1) Assess changes in salinity and ion concentrations in all areas of the IFDM project (A, B, C and D);
2) Assess the spatial distribution of soil salinity in the forage and halophyte areas (C and D); and,
3) Evaluate the effectiveness of surface applications of gypsum on infiltration rates.

Methodology: In order to assess the changes in salinity and chemical composition of the soil, we have been soil sampling (0-5ft, in 1ft increments) twice yearly for the past 3 three years in all areas (A,B,C,D) of the RRR IFDM demonstration project. A hydraulic soil corer (Giddings rig) is used to collect samples at the GPSreferenced locations. In some cases 0-6 inches samples were also collected. Samples were air-dried, sieved through a 2mm (USDA # 10 sieve) and ground for preparation of saturated paste extracts made with distilled water. Soil salinity (electrical conductivity (ECe), pH, boron (B), sodium (Na), calcium (Ca), magnesium (Mg), and sulfate ($S0_4$-S) ion concentrations were measured on the paste extracts and the sodium adsorption ratios (SAR) were calculated. Nitrate (NO_3) and selenium (Se) levels were analyzed on separate extracts. Procedures given in the Western States Laboratory Proficiency Testing Program- Soil and Plant Analytical Methods were used for most of the analyses (Gavlak et al, 1994).

To assess the spatial and temporal variability in soil salinity in Areas C and D, salinity mapping will be conducted each fall using the electromagnetic induction technique ("dual-dipole" EM-38) currently available at California State University- Center for Irrigation Technology (CIT). This technique allows for rapid, high density, aboveground measurements with non-invasive sampling for the determination of depth- averaged (0-2 and 0-4 ft.) soil salinity.

Water infiltration is being measured in Area D (3rd re-use of DW; ECe up to 70 dS/m) where seven years of irrigation with saline-sodic drainage water has degraded the soil structure severely reducing infiltration. For comparison, infiltration is also measured in Area A that has received only freshwater irrigation (canal or wellwater; soil EC $\leq$ 6 dS/m) and is cropped to agronomic plants (e.g. tomatoes, onions, wheat). In Area D, infiltration is measured in plots containing three different halophytic plants (saltgrass, Salicornia, and Atriplex). These differ notably in that saltgrass provides a full vegetative cover over the soil, whereas Salicornia and Atriplex fields have exposed soil. Four replicate plots were established for each area and vegetation type and for each, there are duplicate plots with and without gypsum application (3 ton/acre) for a total of 32 plots.

Results and Discussion:

Figure 3. Red Rock Ranch Sequential DW Re-use Demonstration Project as per Modifications up to July 2003

640 acres (260 ha)

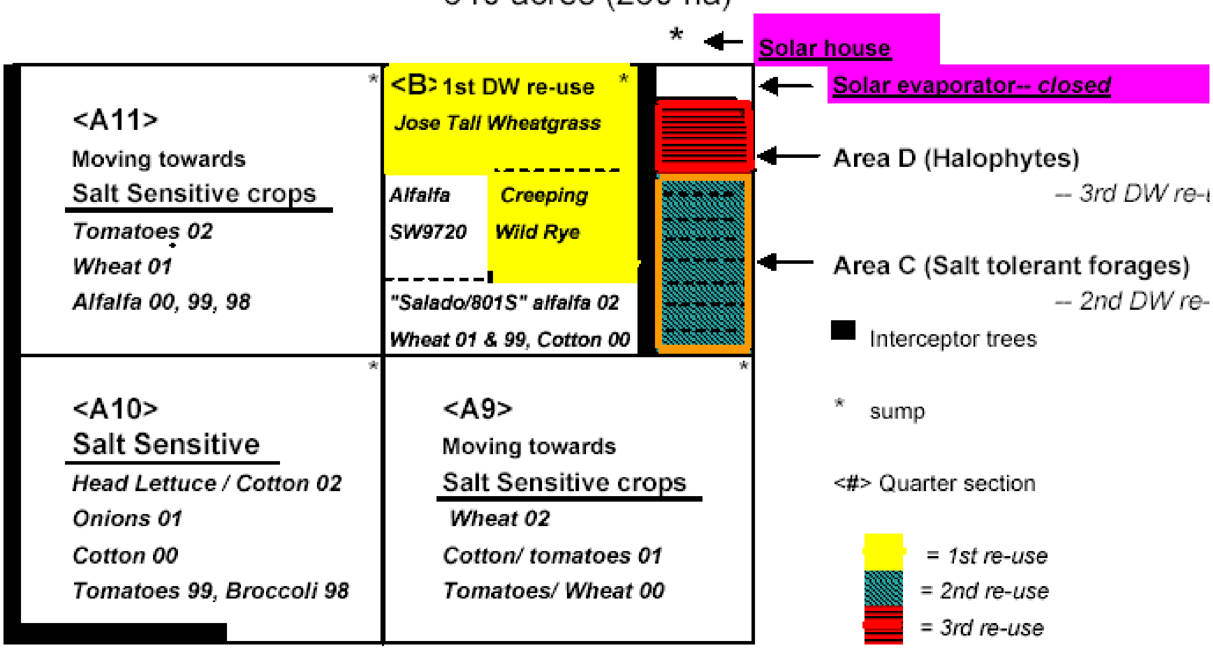


Figure 3 shows the 2003 updated version of the layout of water re-use and crops grown on the RRR IFDM demonstration project. A significant change from the original design showed in **Figure 1**, which may be indicative that the sequential re-use of drainage water is working, is that almost half of the quarter section in Area B is now planted in crops irrigated with fresh canal water. Hence this subsection of the demonstration project can now be re-classified as part of Area A. In 2002 the grower successfully planted head lettuce in subsection A10 which may have only been possible due to the soil improvement achieved with the subsurface drainage system. The other major change from the 1996 design is the closure of the solar evaporator and the testing of a "solar house" and a solar "concentrator". The solar house is an enclosed system which decreases the risk of wildlife access to standing water and allows the collection of clean salt. The solar concentrator is an outdoor system in which enhanced evaporation methods such as nozzles that atomize water are being tested. Markets are currently being sought for the evaporated salt.

Examples of a typical salinity profiles are presented in **Figures 4a** and **b,** along with a summary of the ECe and SAR values for the top foot of soil from fall 2000 to Fall 2002 (**Table 2)**. In Area A, leaching is occurring as indicated by the relatively lower salinity at shallow depths. However, in Area D (3rd re-use of the drainage water), there is extreme salt accumulation (ECe) and sodicity (SAR) in the surface 12 in. of soil (T**able 2**). These extremely high SAR values (>50) represent a sodium-saturated soil, which is prone to severe reductions in water infiltration and permeability (i.e. ponding), particularly when nonsaline winter rains fall (Oster, 2001, 1998). Low soil permeability also contributes to the perched water table which in turn contributes to the inverted salinity profile in Area D.

Table 2. Soil EC and SAR data for the Red Rock Ranch IFDM from 2000 to 2002.

Parameter††	Unit	Fall 2000	Fall 2001	Fall 2002	Avg.† (2000-2002)
FW-irrigagted acreage					
EC	dS/m	4.6 ± 0.4	4.1 ± 7.4	4.5 ± .7	4.3 ± 2.6
SAR	--	6.6 ± 0.7	2.8 ± 0.3	12.4 ± 1.36	9.1 ± 1.1
Area B (1st re-use of DW)					
EC	dS/m	10.9 ± 2.4	10.4 ± 2.4	10.8 ± 3.5	10.5 ± 2.2
SAR	--	21 ± 4.3	36.6 ± 17.8	20.76 ± 4.74	25.1 ± 5.6
Area C (2nd re-use of DW)					
EC	dS/m	14.2 ± 2.2	15.6 ± .9	16.4 ± 1.1	14.5 ± 1.5
SAR	--	27.2 ± 4.7	14.3 ± 2.6	29.8 ± 1.96	28.1 ± 3.4
Area D (3rd re-use of DW)					
EC	dS/m	55.6 ± 7.6	38.4 ± 2.1	41.5 ± 3.3	40.7 ± 4.1
SAR	--	99.5 ± 11.6	50.8 ± 2.4	79.0 ± 3.9	73.6 ± 5.7

†Average 2000 - 20002 also includes late spring measurements
††EC, B, Cl, and SO_4 were done on saturated paste extracts and Se and nitrate-N on dry soil.

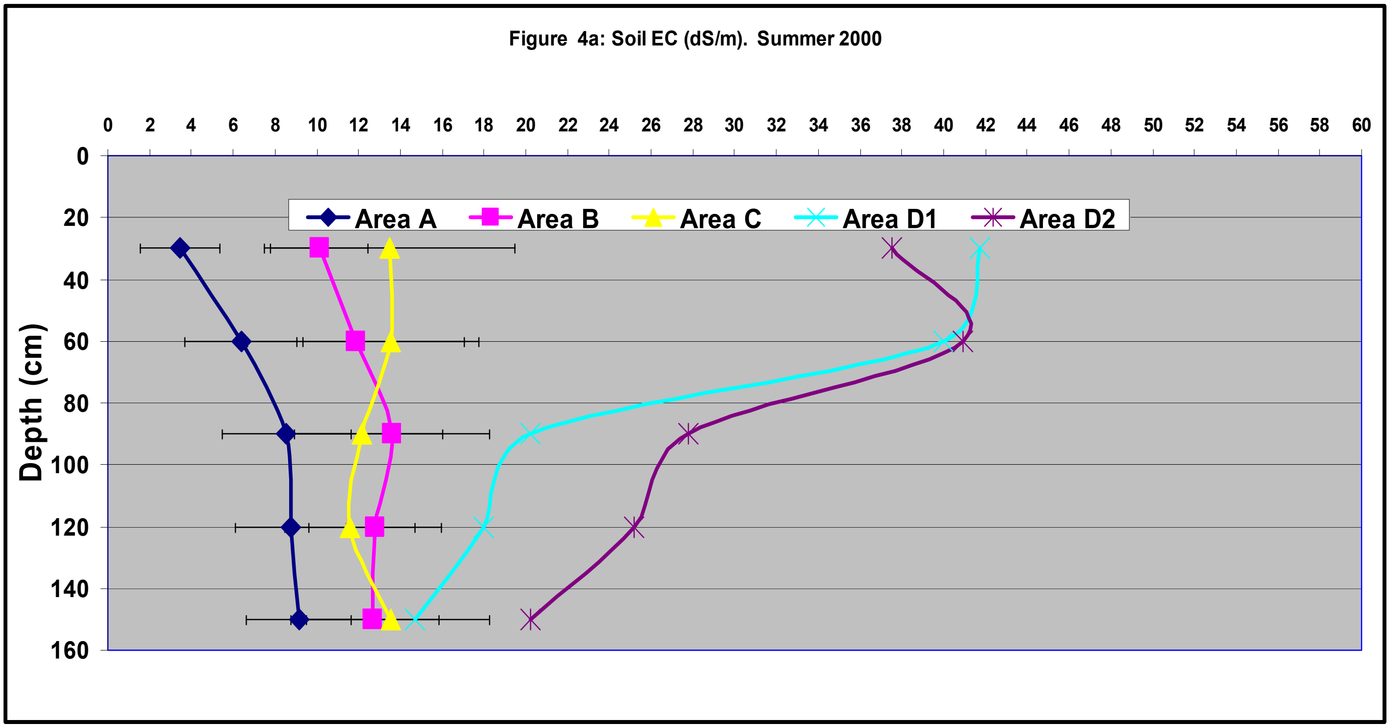


Figure 4a: Soil EC (dS/m). Summer 2000
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60
Depth (cm)
0 20 40 60 80 100 120 140 160
Area A
Area B
Area C
Area D1
Area D2

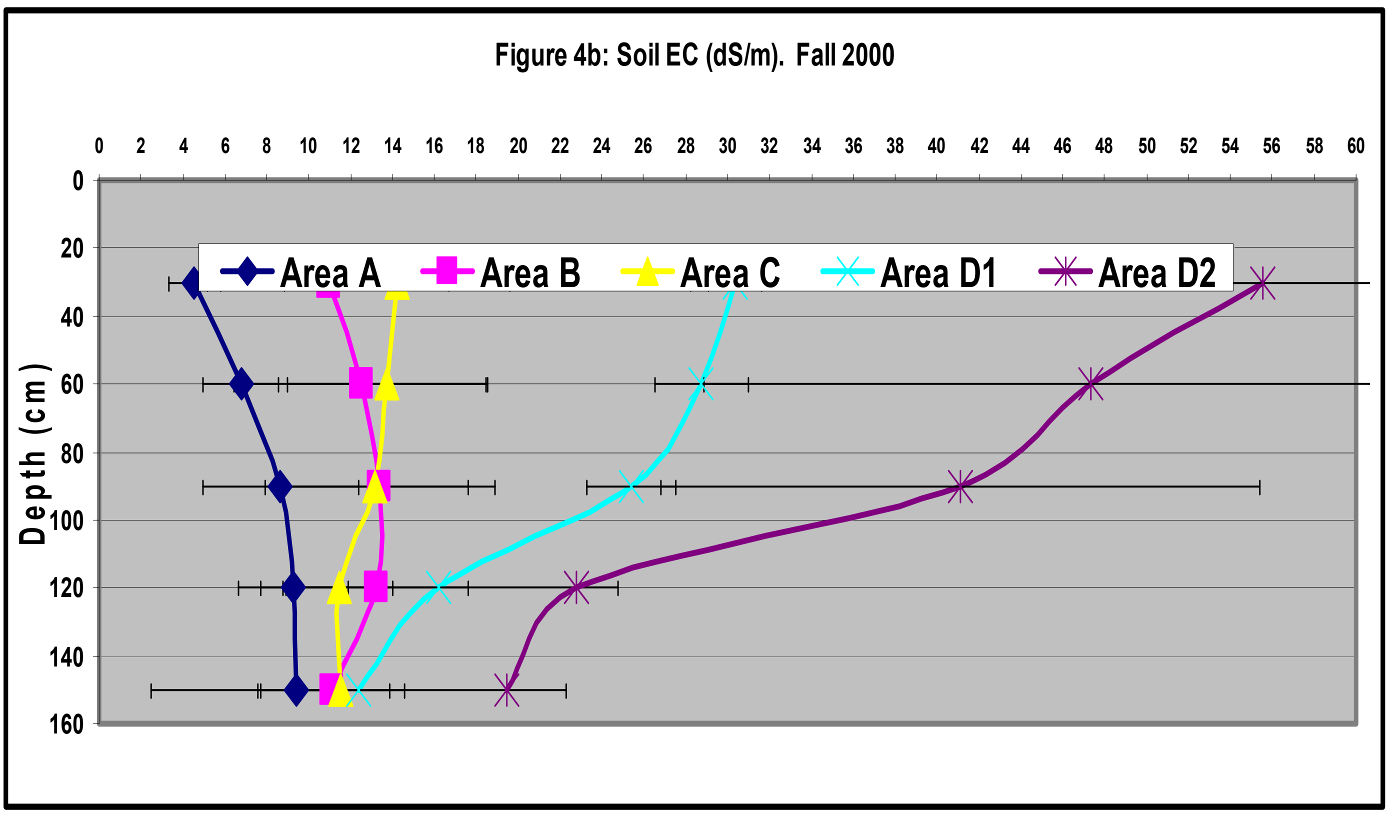
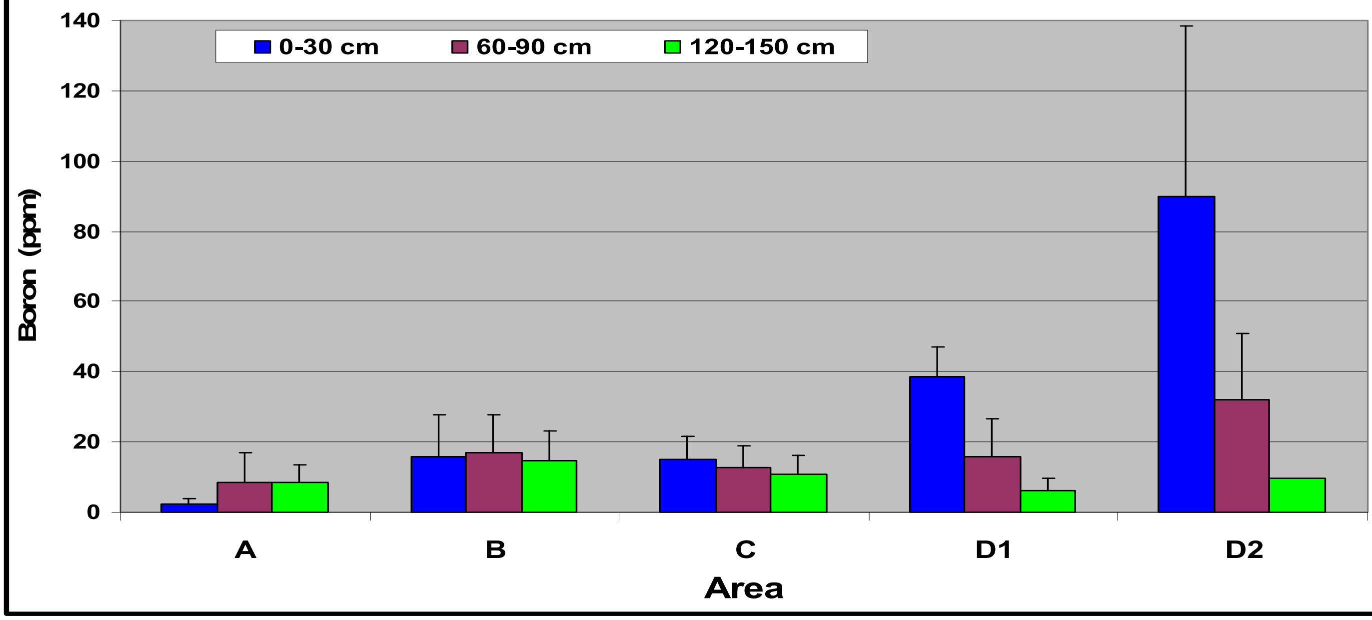


Figure 4b: Soil EC (dS/m). Fall 2000
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60
Depth (cm)
0 20 40 60 80 100 120 140 160
Area A
Area B
Area C
Area D1
Area D2

Figure 5: Boron in Soil. Fall 2000.



Similar to salinity, boron concentrations in soil increased with each sequential use of saline drainage water (i,e. Area A<Area B< Area C< Area D). For example, in Fall 2000 (**Figure 5**), in Area A, boron concentrations were lowest in the surface foot of soil indicating leaching. In Areas B and C, boron concentrations were similar at all depths and higher than in A. In Area D, boron in the top foot (30 cm) averaged 38 (D1) and 90 ppm (D2m) for Fall 2000. The higher boron concentration in D2 may be due to increased capillary flow resulting from the open plant canopy for Salicornia as compared to saltgrass.

Table 6: Mean of 2000 and 2001 summer and fall ion concentrations and pH for top 12 inches of soil.

Site	Plant species		Se (ppm)	NO3-N (ppm)	SO4 (ppm)	Cl (meq/L)	Na (meq/L)	Ca (meq/L)	Mg (meq/L)	pH
A	Agronomic crops	Mean	**0.87**	**22.5**	**939**	**9.4**	**18.8**	**19.0**	**3.4**	**7.6**
		s.e	0.06	8.2	178	2.6	4.2	3.0	0.5	0.1
B	Salt tolerant crops	Mean	**1.40**	**9.2**	**2261**	**37.7**	**107.4**	**44.1**	**7.4**	**7.4**
		s.e	0.17	4.6	484	10.2	31.9	7.6	1.1	0.2
C	Salt tolerant forages	Mean	**1.95**	**8.4**	**3319**	**43.2**	**109.7**	**54.1**	**11.3**	**7.9**
		s.e	0.14	5.3	336	10.5	22.0	6.9	1.3	0.1
D1	Halophyte (saltgrass)	Mean	**3.78**	**34.0**	**7238**	**186.6**	**338.8**	**99.1**	**21.4**	**7.7**
		s.e	0.31	6.0	1418	21.1	9.8	6.4	2.8	0.1
D2	Halophyte (Salicornia)	Mean	**7.93**	**30.8**	**8966**	**258.3**	**445.5**	**191.8**	**33.1**	**8.3**
		s.e	1.14	14.5	944	59.1	82.4	69.2	7.0	0.1

**EC, B, Cl, SO4, Na, Ca, Mg, pH done on saturated paste extract. Se = total.*

During 2000- 2001, soil pH in the top twelve inches of soil ranged from 7.2 to 8.4 (**Table 6)**. In area A, sodium and calcium levels were similar. However, in areas irrigated with saline-sodic drainage water, sodium levels were more than three times that of the calcium. Generally, calcium levels greater than or at least similar to sodium levels are desirable for soil structure favorable for water percolation and crop growth. Similar increasing trends were observed for chloride and sulfate concentrations in moving from soils receiving fresh canal water in Area A to the soils in Area D with the halophytes (**Table 6).** Selenium concentrations in Area A were less than 1 mg/kg, but in Area D they reached almost 8 mg/kg which poses a significant risk to wildlife when irrigation water ponds in this field. Hence, a current practice is to irrigate sections of Area D, such as the field planted with Atriplex, with a sprinkler system rather than flooding. It is noteworthy that for the period 2000-2001, the fields with the lowest average nitrate concentrations of approximately 9.0 ppm were observed in Areas B and C, which were planted in salt tolerant crops and forages (**Table 6**).

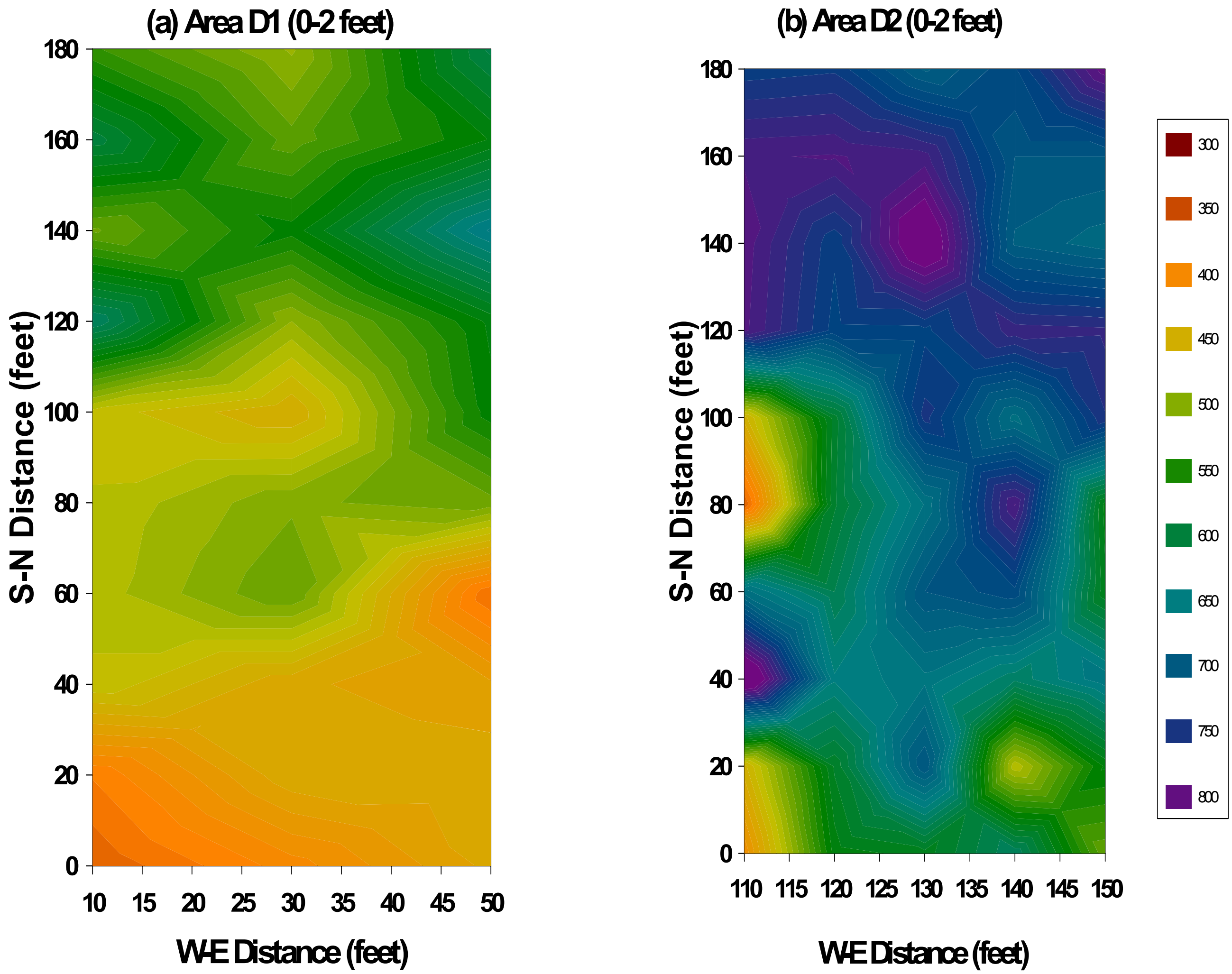
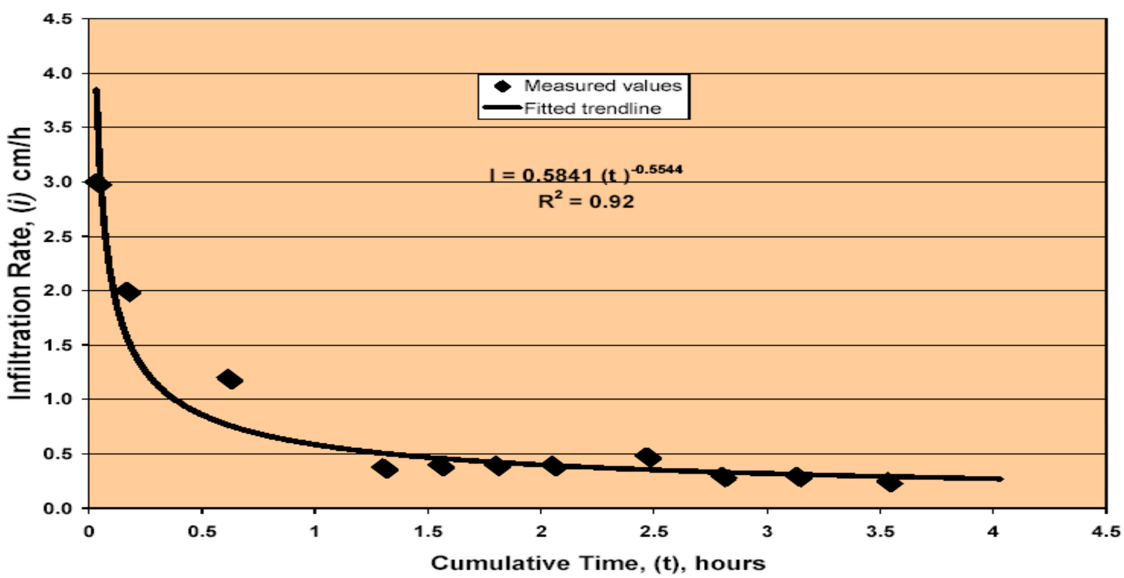


Figure 6. Apparent electrical conductivity (ECa) within the top 2 feet of soil measured with the EM-38 for (a) Area D1 and (b) Area D2. ***Units are in dS/m.***

Salinity maps for fields in Area D, compiled with data from EM 38 measurements, are shown in **Figure 6.** These maps are very useful for monitoring the relative changes in the spatial variability of soil salinity over time. It must be noted that the information depicted in figure 6 is the apparent electrical conductivity (ECa) and as so the influence of soil moisture content, texture and organic matter are incorporated in these values. Hence, unless the data is ground-truthed, a task which has been included as part of research for the next rounds of EM measurements, the maps presented in Figure 6 should be used primarily for comparison of relative, rather than absolute, soil salinity values. Based on this assumption, it would appear that the D2 fields (Salicornia) are relatively more saline than the fields in D1 (saltgrass). More importantly, there is wider range of soil salinity in D2 (**Figure 6b)** than in the D1 fields. Interestingly, both sets of fields have a trend of relatively lower salt concentrations at their southern ends than at the northern ends which is directly correlated to the flow direction of flood irrigation system and the recent conversion to sprinkler irrigation in the entire northern half of the area. This may imply that there is a need for more water at the northern (tail end of the irrigation) end of the field so as to ensure adequate leaching of salts.

Based on the findings from initial infiltration experiments conducted in summer 2001, we have chosen double ring infiltrometers for our field measurements. Currently, we are using various curve–fitting approaches to analyze the time and depth data collected from the ring infiltration measurements in 2002. In our first approach we determine the steady rate infiltration (i_s), also referred to as *steady-state infiltrability* or as the *final infiltration capacity* (Hilllel, 1998). The steady rate infiltrations are examined rather than the initial or "early time" infiltration. Soil infiltrability is relatively high in the early stages of infiltration, particularly where the soil is dry, but then it tends to decrease monotonically and eventually approaches an asymptotic constant infiltration rate (**Figure 7**). Hence, by comparing the "late time" steady rate infiltrations, care is taken to ensure that the values being compared are not influenced by the initial moisture content of the plots or by the differences in the ponding head in the ring infiltrometers. For the infiltration experiments conducted in summer 2002, we found that steady state infiltrability rates (i_s), which generally were attained after 2.5 to 3 hours, averaged at 2.1 cm h^{-1} and 1.7 cm h^{-1} for the gypsum plots in areas A and D, respectively. For the non-gypsum i_s values ranged from 0.7 to 1.0 cm h^{-1} for both areas.

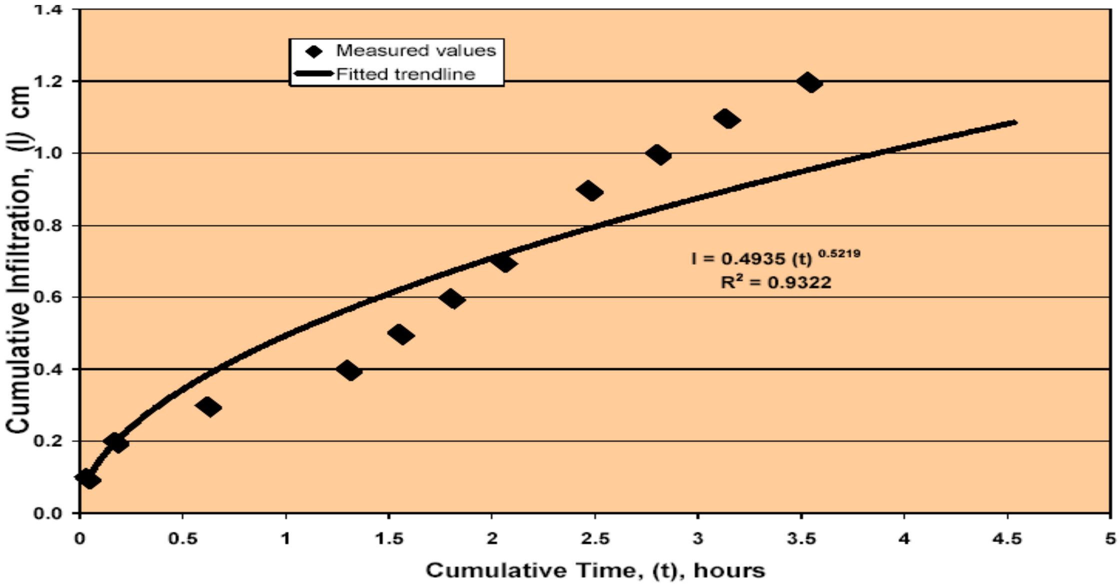
Figure 7. Example of measured infiltration rates with fitted trend line used to determine steady rate infiltration for a non gypsum plot in area A



In our second approach, cumulative infiltration (*I*) over cumulative time (*t*) will be determined using (Jury et al., 1991): **I = *a t b*** **Eqn. (1)**

where *a* and *b* are empirical constants (**Figure 8**). Derivatives of Eqn. 1 will be taken at 2 and 4 hours to estimate infiltration rates i_2 and i_4.

Figure 8: Example of measured cumulative infiltration with fitted trendline used to determine equation 1 for a non gypsum plot in area A.

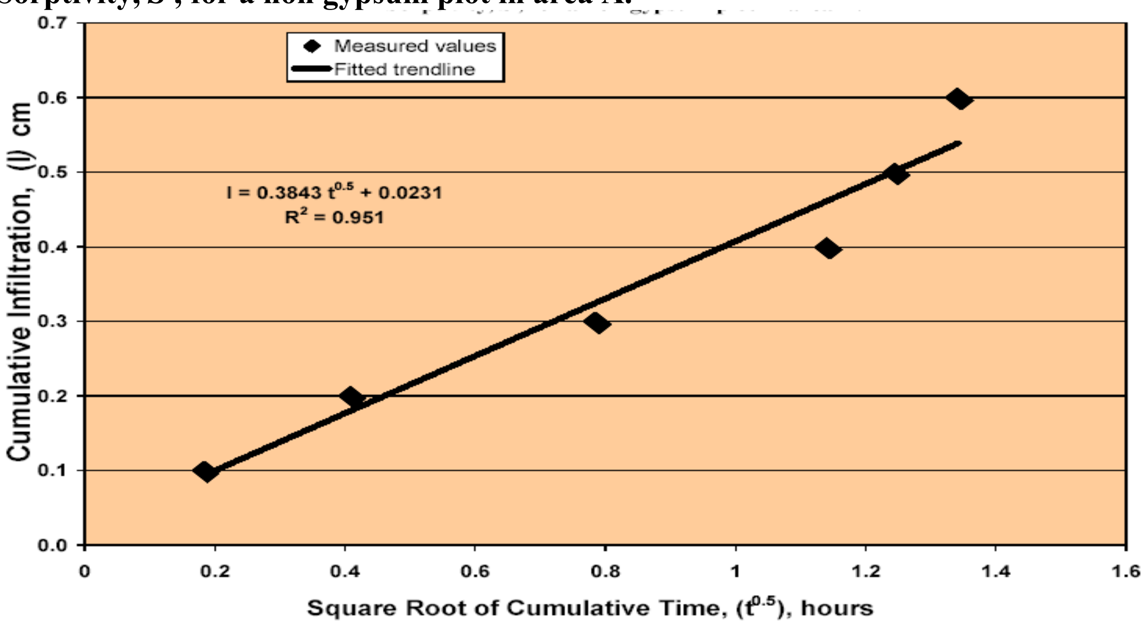


In our final method, we will determine the sorptivity (S) of the soil according to (Bower, 1986):

$$I = S\,t\,0.5 + B \qquad \textbf{Eqn. (2)}$$

where: S is a term that depends on the pore configuration of the soil, the initial water content of the soil, and the ponding head; and B is a factor related to the hydraulic conductivity and the elapsed time from water application. Values of S will be determined from the infiltrometer measurements by plotting I vs. $t0.5$ for the portion of the test where I increases essentially linearly with $t0.5$ and S is evaluated as the slope of the straight line portion of the curve (**Figure 9**).

Figure 9: Example of measured cumulative infiltration with fitted trend line used to determine Sorptivity, *S* , for a non gypsum plot in area A.



General Comments on the IFDM Demonstration Project

- ***Area A (canal water)*** seems to be benefiting from the use of subsurface drainage. Soil salinity, boron, and SAR are lowest in the surface 30 cm which represents a substantial part of the rooting zone for annual crops.
- ***Areas B and C (1^{st} and 2^{nd} reuse)*** could benefit from more leaching. This could include increased application of tailwater to Area B and in both B and C, increasing the amount of applied water (drainage in the growing season) and fresh water (rain or irrigation) in the winter.
- ***Area D (3^{rd} re-use)*** shows extreme salt accumulation in the surface layer, and little evidence of leaching. Water application is being increased but is limited by poor infiltration in this area. A possible remedy would be to eliminate the 3^{rd} re-use of drainage water and have only two. The first re-use area would have salt tolerant crops, or less tolerant forages; and the second re-use area would have forages of higher salt tolerance, or halophytes, depending on salinity of the drainage water, soil texture, and resulting soil salinity.
- It is our hope that by comparing infiltration rates in the drainage water re-use areas to those under conventional irrigation with non-saline water, we can begin to assess the long term impacts of irrigation with saline-sodic drainage water on soil structure and permeability, and eventually to formulate management plans that utilize gypsum or sulfur, and possibly organic amendments, to minimize soil degradation.

Future Work

- We have reduced our soil core sampling to the just the fall season over the next two years for determination EC, SAR, pH, B, Se, Ca, Mg, Na,NO_3, Cl, and SO_4 in 1ft increments to a depth of 5ft. This is primarily in response to the relatively better depiction of the spatial variability soil salinity available with the EM-38 equipment.
- Data obtained with the EM-38 equipment will be used with “ESAP” software developed by J.R. Rhoades at the USDA Salinity Lab to determine locations for ground-truthing soil sampling, and converting the EM data to absolute soil salinity values
- The infiltration parameters will be monitored twice per year for the next two years.

Acknowledgement

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Projector Director: Sharon E, Benes Ph.D.

References

Bower, H. 1986. Intake Rate: Cylinder Infiltrometer. Chapter 32 in *Methods of Soil Analysis Part 1- Physical and Mineralogical Methods*. Agronomy Monograph no.9. ASA-SSSA. WI. USA

California Regional Water Quality Control Board Central Valley Region (1994). Waste Discharge Requirements for Westside Resource Conservation District and Diener Family Trust Red Rock Ranch Agroforestry Demonstration Project. Order No. 94-298.

Gavlak, R.G., D. A. Horneck, and R. O. Miller. 1994. Plant, Soil and Water Reference Methods for the Western Region. WREP 125.

Grattan, S.R. and J.D. Oster. 2003. Use and reuse of saline-sodic water for irrigation of crops. In: Crop Production in Saline Environments: Global and Integrative Perspectives (S.S. Goyal, S.K. Sharma and D.W. Rains, eds). Haworth Press, New York pp 131-162.

Grattan, S.R. et al. (1999). Technical Report on Drainage Water Reuse. M. Alemi and J. Letey (Coordinators). San Joaquin Valley Drainage Implementation Program and the University of California Salinity/Drainage Program. California State Department of Water Resources 91 pp

Grattan, S.R. (1997). Limitations and consequences of recycling drainage water for irrigation over the long-term. 27th IAHR Congress Proceedings. San Francisco, CA. Aug. 10 – 15.

Hillel, D. 1998. *Environmental Soil Physics*. Chapter 14. Academic Press. 771 pp. California, USA.

Jury, W.A., W.R. Gardner and W.H. Gardner. 1991. *Soil Physics*. 5th Ed. John Wileyand Sons. New York. NY.

Letey J, Roberts C, Penberth M, Vasek C. 1986. An Agricultural Dilemma: Drainage Water and Toxics Disposal in the San Joaquin Valley. UC Agricultural Experiment Station Spec. Publ. 3319. 56 p.

Letey J. (2000). Soil salinity poses challenges for sustainable agriculture and wildlife. CA Agriculture 54(2), Mar-April 2000. pp. 43-48.

Oster, J.D. (2001). Sustainable use of saline-sodic drainage water. Proceedings CA Plant & Soil Conference, CA chapter of the ASA and the CA Plant Health Association. Feb.7-8. Fresno, CA. pp. 1-8.

Oster, J.D., and N.S. Jayawardane (1998). Agricultural Management of sodic soils, Ch. 8. <u>In:</u> M.E. Sumner and R. Naidu (eds.). Sodic Soils: Distribution, Management, and Environmental Consequences. Oxford Univ. Press

San Joaquin Valley Drainage Implementation Program (1998). Drainage Management in the San Joaquin Valley. A Status Report. Feb. 1998, 65 pp.

San Joaquin Valley Drainage Implementation Program. (1999). Final report of the Drainage Reuse Technical Committee. S.R. Grattan, Chair. 81 pp.

Van Schilfgaarde (1990). Irrigated agriculture. Is it sustainable? *<u>In</u>*: Agricultural Salinity Assessment & Management. K.K. Tanji (ed.). Amer. Soc. of Civil Engineers, pp. 584-594.